

# Synchrotron Radiation as the Source of GRB Spectra, Part I: Theory.

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**Abstract.** We investigate synchrotron emission models as the source of gamma ray burst spectra. We show that allowing for synchrotron self absorption and a “smooth cutoff” to the electron energy distribution produces a wide range of low energy spectral behavior. We show that there exists a correlation between the value of the peak of the  $\nu F_\nu$  spectrum,  $E_p$ , and the low energy spectral index  $\alpha$  as determined by spectral fits over a finite bandwidth. Finally, we discuss the implications of synchrotron emission from internal shocks for GRB spectral evolution.

## INTRODUCTION

It has been suggested (e.g. [4]) that synchrotron emission is a likely source of radiation from GRBs, and later shown [11] that an optically thin synchrotron spectrum is a good fit to some bursts. However, some features seen in the low energy portion of GRB spectra can not be explained by the simple synchrotron model (SSM) - optically thin synchrotron emission from a power law distribution of relativistic electrons with a minimum energy cutoff. This model predicts that the asymptotic value of the low energy photon index,  $\alpha$ , should be a constant value of  $-2/3$ . However, the data show an  $\alpha$  distribution with a mean of about  $-1.1$  and a standard deviation of about 1. Furthermore, there are a significant fraction of bursts with  $\alpha > -2/3$  - above the so-called “line of death” [10]. In addition, spectral evolution of  $\alpha$  and the peak of  $\nu F_\nu$ ,  $E_p$ , are inconsistent with an instantaneous optically thin synchrotron spectrum in an external shock model [3]. Consequentially, other models - usually involving inverse compton scattering [2], [5] - were invoked to explain these “anomolous” spectral behaviors.

In this paper, we discuss how GRB spectra can be accomodated by synchrotron emission, including those spectra not explained by the SSM. We discuss the various spectral shapes from a general form for synchrotron emission, allowing for the possibility for self-absorption and a smooth cutoff to the electron energy distribution, and show that these models fit GRB spectra well. We show there is a correlation between  $\alpha$  and  $E_p$  as determined by fits using the Band [1] (and similiar) spectral forms. Finally, we briefly discuss the variety of spectral evolution behaviors seen

in GRBs in the context of synchrotron emission. In Part II (Lloyd et al., these proceedings, [7]), we compare our theoretical predictions with the data and show how synchrotron emission can explain the spectral behavior of GRBs.

## SYNCHROTRON EMISSION

The general form for an instantaneous synchrotron spectrum for a power law distribution in the electron energy with a sharp cutoff,  $N(E) = N_o E^{-p}$ ,  $E > E_{min}$ , is given by [9]

$$F_\nu = A \nu^{5/2} \left[ \frac{I_1}{I_2} \right] \times [1.0 - \exp[-Q \nu^{-(p+4)/2} I_2]] \quad (1)$$

$$I_1 = \int_0^{\frac{\nu}{\nu_{min}}} dx x^{(p-1)/2} \int_x^\infty K_{5/3}(z) dz, \quad I_2 = \int_0^{\frac{\nu}{\nu_{min}}} dx x^{p/2} \int_x^\infty K_{5/3}(z) dz \quad (2)$$

$A$  is the normalization and contains factors involving the perpendicular component of the magnetic field,  $B_\perp$ , bulk Lorentz factor,  $\Gamma$ , and number of electrons,  $N_o$ . The frequency  $\nu_{min} = (\Gamma E_{min}^2 B_\perp 3e)/(m^3 4\pi c^2)$ . The parameter  $Q$  represents the optical depth of the medium (for example, if  $\nu \gg \nu_{min}$ , the photon spectrum will be absorbed at the frequency  $\nu_{abs} \sim Q^{2/(p+4)}$ ). The high energy asymptotic behavior is the usual  $F_\nu \propto \nu^{-(p-1)/2}$ . The low energy asymptotic forms of the function depend on the relative values of  $\nu_{min}$  and  $\nu_{abs}$ :  $F_\nu \sim \nu^{5/2}$  for  $\nu_{min} < \nu \ll \nu_{abs}$ ,  $F_\nu \sim \nu^2$  for  $\nu \ll \min[\nu_{abs}, \nu_{min}]$ ,  $F_\nu \sim \nu^{1/3}$ , for  $\nu_{abs} < \nu < \nu_{min}$ .

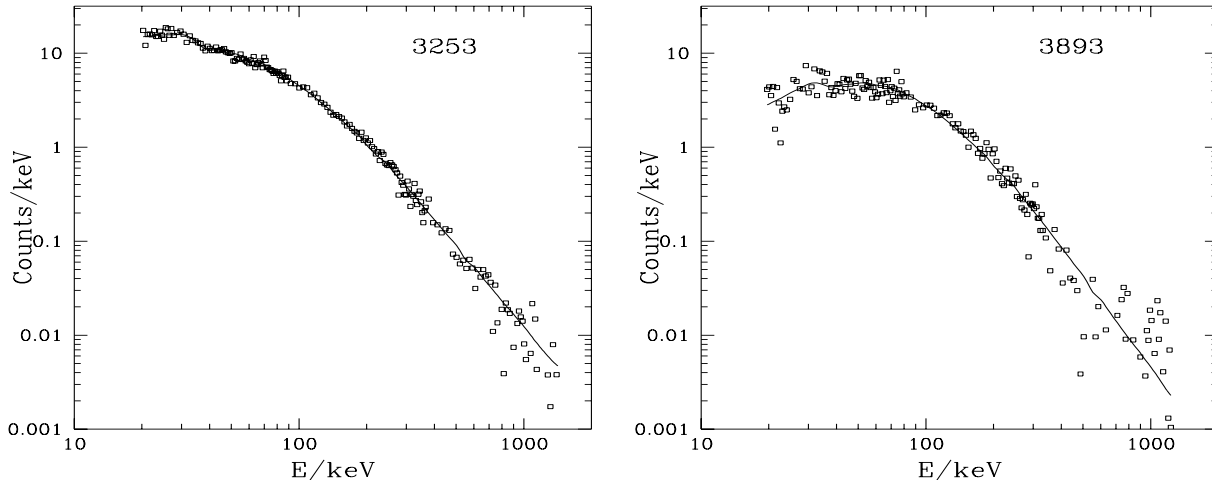
Note that we do not address the case of cooling electrons, which will have the effect of increasing the electron power law distribution index  $p$  by 1,  $p \rightarrow p + 1$  at some characteristic cooling energy.

## THE ELECTRON DISTRIBUTION

In most models of synchrotron emission, the electron distribution is modeled by a power law with a sharp cutoff at some minimum energy (as done in the previous section). This is not a realistic (and may even be an unstable) distribution. We characterize the electron distribution by the following equation:

$$N(E) = N_o \frac{(E/E_*)^q}{1 + (E/E_*)^{p+q}} \quad (3)$$

where  $E_*$  is some critical energy that characterizes where the electron distribution changes. For  $E \gg E_*$ ,  $N(E) \propto E^{-p}$ , while for  $E \ll E_*$ ,  $N(E) \propto E^q$ . Hence,  $q$  characterizes the “smoothness” of the cutoff. This has a significant impact on the low energy portion of the synchrotron spectrum. An optically thin synchrotron spectrum takes the form:



**FIGURE 1.** Spectra of two GRBs; the solid line shows the synchrotron model fit. An optically thin model is the best fit to 3253 (left), while an optically thick model best describes 3893 (right).

$$F_\nu = A(\nu/\nu_*)^{(q+1)/2} \int_0^\infty dx \frac{x^{-(q+p)/2}}{1 + ((\nu/\nu_*)^{(q+p)/2} x^{(p+q)/2})} \int_x^\infty K_{5/3}(z) dz \quad (4)$$

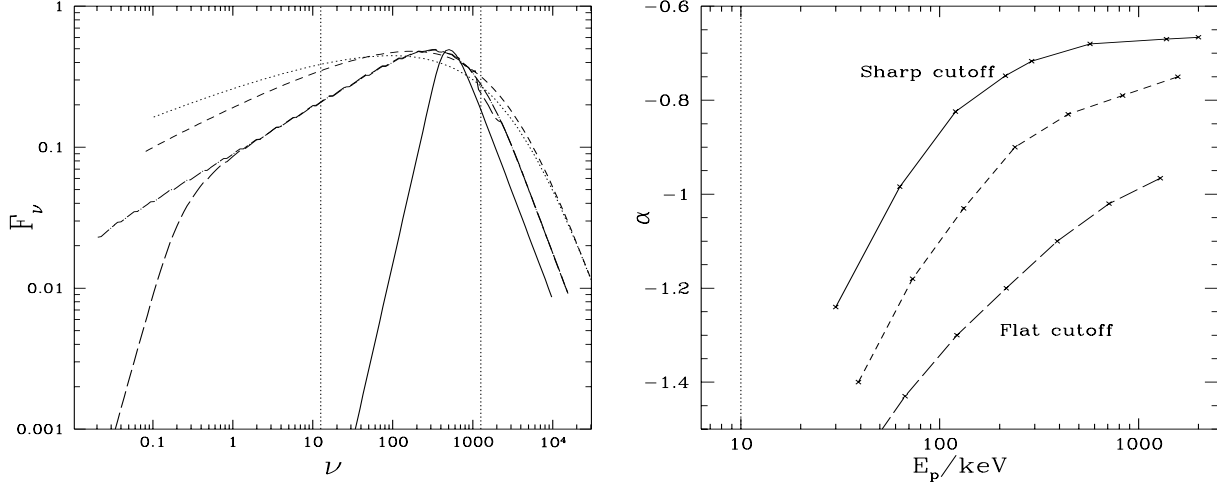
where  $\nu_* = c_1 B_\perp E_*^2$ . Depending on the smoothness of the cutoff, the spectrum of the emitted photons can change significantly. The peak of the spectrum is shifted to lower energies as the cutoff becomes smoother ( $q$  smaller), and the width of the spectrum increases, which implies that it takes longer for the spectrum to reach its low energy asymptotic value.

## SPECTRAL FITS

Synchrotron emission models fit the GRB data well. We fit 11 bursts with 256 channel energy resolution to the synchrotron spectral forms described above. Five of these bursts have a low energy photon index (as determined by fitting a Band spectrum) above the “line of death” for optically thin synchrotron emission; that is,  $\alpha > -2/3$ . In all of these cases, we found that *including an absorption parameter will accommodate the hardness of the low energy index*, and provided the best fit. Figure 1 shows the spectra for 2 GRBs in our sample (burst triggers 3893 and 3253). A self-absorbed spectrum in which the absorption frequency just enters the BATSE window best fits 3893, while an optically thin spectrum is the best fit to 3253. For a more complete discussion of the spectral fits, see [8].

## A RANGE OF SPECTRA

Figure 2a shows the many types of low energy spectral behavior one can obtain from the above synchrotron models, normalized to the peak of  $F_\nu$  (at 500 keV).



**FIGURE 2. Left Panel:** Synchrotron spectra for different values of the optical depth and smoothness of the electron cutoff. Optically thin spectra are shown by the the dot-dashed line, the dotted line, and the short-dashed line for a sharp ( $q = \infty$ , SSM), an intermediate ( $q = 2$ ) and flat ( $q = 0$ ) cutoff to the  $e^-$  distribution, respectively. The solid and long dashed lines show the self-absorption cutoff when  $\nu_{abs} > \nu_{min}$  and  $\nu_{abs} < \nu_{min}$ , respectively. The vertical lines mark the BATSE window. **Right Panel:** The correlation between  $\alpha$  and  $E_p$  for a spectrum with a sharp (solid line), intermediate (short dashed), and flat (long dashed) cutoff to the  $e^-$  distribution.

The vertical lines mark the approximate width of the BATSE spectral window.

Now, the  $\alpha$  distribution will depend largely on how quickly the spectrum reaches its low energy asymptote or how well spectral fits can determine the asymptote. As  $E_p$  moves to lower and lower energies, we get less and less of the low energy portion of the spectrum; in this case, our spectral fits probably will not be able to determine the asymptote and will measure a lower (softer) value of  $\alpha$ . [Preece et al. [10] pointed out this effect and attempt to minimize it by defining an effective  $\alpha$ , which is the slope of the spectrum at 25keV (the edge of the BATSE window). However, a correlation between  $\alpha_{eff}$  and  $E_p$  will still exist if the asymptote is not reached well before 25keV.] This difficulty becomes more severe the smoother the cutoff to the electron distribution, because the spectrum takes longer to reach its asymptote. To test this, we produce sets of data from optically thin synchrotron models with different parameters ( $\nu_{min}$ ,  $q$ , etc.), all of which have a low energy asymptote of  $-2/3$ . We fit a Band spectrum to this data (to be conservative, we extended the range of BATSE's sensitivity to 10 keV). Figure 2b shows the value of the asymptote as determined by the Band spectrum, as a function of  $E_p$ , for different degrees of the smoothness of the electron energy distribution cutoff. Not surprisingly, there is a strong correlation between the value of  $E_p$  and the value of the “asymptote”,  $\alpha$ , as determined by a Band fit to the data. We can use this relationship and knowledge of the  $E_p$  distribution to determine the resultant distribution for  $\alpha$ . This is discussed in Part II [7].

## SPECTRAL EVOLUTION

The behavior of the spectral characteristics with time throughout the GRB can give us information about the environment of the emission region and conceivably constrain the emission mechanism. Given the apparent correlation between  $\alpha$  and  $E_p$  induced by the fitting procedure, we expect evolution of  $\alpha$  (obtained from such fits) to mimic the behavior of  $E_p$  in time during a pulse or spike. Note, however, if each pulse in the time profile is a separate emission episode (as in an internal shock scenario), parameters such as  $q$  and the optical depth can vary from shock to shock; this can create a change in  $\alpha$  from pulse to pulse, independent of  $E_p$ .

## CONCLUSIONS

Synchrotron emission can produce a variety of GRB spectral shapes, particularly when one allows for a smooth cutoff to the electron distribution and includes effects of self-absorption. In addition, we expect a relationship between  $\alpha$  and  $E_p$ , as a consequence of the fitting procedure; this will have implications for the observed distributions and temporal evolution of spectral parameters. We test this model against the data in Part II [7].

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